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Human factors applied to alarm panel modernization of nuclear control room

Isaac José Antonio Luquetti dos Santos [a,*], Marcos Santana Farias [a], Fernando Toledo Ferraz [b], Assed Naked Haddad [c], Suzana Hecksher [b]

[a] National Nuclear Energy Commission, Nuclear Engineering Institute, Cidade Universitária, Ilha do Fundão, Rio de Janeiro 21941-906, Brazil
[b] Fluminense Federal University, Department of Production Engineering, São Domingos Niterói, Rio Janeiro 24210-240, Brazil
[c] Rio Janeiro Federal University, Environmental Engineering Program, Rio Janeiro 20000-000, Brazil

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ABSTRACT

Human factors deal with issues related to humans, their behavior and the physical aspect of the environment in which they work. A control room is a complex system where operators perform plant operation using control systems and carry out monitoring and administrative responsibilities. For safe operation of industrial installation, the performance of the control room crew plays an important role. In this respect, a well designed control room is crucial for safe and efficient operation. The aim of this paper is to propose a methodological framework applied to nuclear control room evaluation, through participatory ergonomics, using operator activity analysis and human factors questionnaire as aid tools. We describe a case study in which the methodology framework was used in the evaluation process of a nuclear control room. The information gathered made possible a series of recommendation for the adequacy of the control room design, assisting in the safety assessment of the nuclear plant operation and justifying the alarm panel modernization.

1. Introduction

Ergonomics is an inter-disciplinary research field that focuses on improving the functioning of the human–technology interaction with regard to safety. This is accomplished by taking into account the strengths and weaknesses of human performance. The goal of the ergonomics is to achieve the best possible match between products and users, in the context of the task to be performed. The ergonomics incorporation in the system design, interfaces and equipment offers a lot of opportunities for improvements with regard to system effectiveness, efficiency, reliability and safety (Luquetti dos Santos, Teixeira, Ferraz, & Carvalho, 2008).

Human factors are a body of scientific factors about human characteristics, covering biomedical, psychological and psychosocial considerations, including principles and applications in the personnel selection areas, training, aid tools for job performance and human performance evaluation (NUREG 0700, 2002). The human factors engineering (HFE) is the application of knowledge about human capabilities and limitations to plant, system and equipment design, in order to ensure that the plant, system design, human tasks and work environment are compatible with the sensory, perceptual, cognitive and physical attributes of the personnel who operate, maintain, and support it (NUREG 0711, 2002). Definitions of ergonomics and human factors are complementary, making reference to human capacities and limitations, work activity, work system, environmental conditions and safety.

According to Gatto, Mól, Luquetti dos Santos, Jorge, and Legey (2013), ergonomics and human factors research field find direct application in the design or upgrade of industrial control rooms, aiming to improve operational safety and reliability. This research field deals with the evaluation of human behavior during operation experiments, by analyzing whether operators are able to track adequately variables' indications, to detect and identify correctly abnormal operational conditions from the alarms indications, and to act promptly to recover normal conditions.

A control room is defined as a functional entity with an associated physical structure, where the operators carry out centralized control, monitoring and administrative responsibilities (ISO 11064, 2000). Most industrial installations have one or several control rooms that function as safety critical barriers against major hazards. It is thus of vital importance that the control room and human–system interfaces should be designed according to human factors principles.

* Corresponding author. Tel.: +55 21 21733846.
E-mail addresses: luquetti@ien.gov.br, ijals@ig.com.br, jaeron@bol.com.br (I.J.A. Luquetti dos Santos).

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The aim of human factors engineering (HFE) is to ensure that the human factors requirements have been satisfactorily integrated into design, development and evaluation of the control room; ensure the necessary means for operators to perform their tasks safely; ensure that the tasks to be performed by operators are correctly specified; ensure that procedures and training requirements are consistent with desired performance; ensure that control room design is consistent with the cognitive characteristics of operators, enabling a compatible human performance with the desired mission; minimize human error; make available adequate information about the status of systems, enabling the execution of tasks by operators during normal and emergency situations. The principal technical document in nuclear area that provides an internationally accepted technical basis for human factors engineering (HFE) is the NUREG 0711 (2002). The approach used in this document defines the implementation of a human factors engineering program in four phases: planning and analysis, design, verification/validation, implementation and operation. In these phases are inserted the elements shown in Fig. 1. In each phase, the following item are implemented: operational experience review, reference system analysis, functional requirement analysis, functions allocation, task analysis, human centered design, procedure development, training; verification/validation process; monitoring human performance.

The phase related to control room design defines physical arrangement of the control room, layout of the control desk, basic requirements of the human–system interfaces, definition of systems to be monitored in the control desk and basic requirements of environmental conditions. The verification and validation process guarantee that all necessary controls, alarms and human–system interfaces have been included in the control room design, so that operators can performance efficiently the tasks in all modes of operation.

Questionnaire is a series of written questions and inexpensive way of gathering quantitative data that could be used to confirm hypotheses. Different methods can be used as quantitative and qualitative tool to evaluate systems and human performance, such as human factors questionnaire, analytic hierarchy process (AHP) and fuzzy logic. Analytic hierarchy process (AHP) is a decision-aiding tool for dealing with complex, unstructured, and multiple-criteria discrete decisions (Saaty, 1996). Since its initial development, AHP has been applied to a wide variety of decision areas, such as aviation, nuclear and manufacturing.

According to Park and Lee (2008), numerous methods to quantitatively estimate the human error probability (HEP) have been developed. This study suggests a method using an analytic hierarchy process (AHP), which quantifies the subjective judgment and confirms the consistency of collected data.

Fuzzy set theory was designed to mathematically represent uncertainty and provide formalized tools for dealing with the imprecision intrinsic to many problems. Fuzzy can be used in many areas in which human judgment, evaluation or decision are

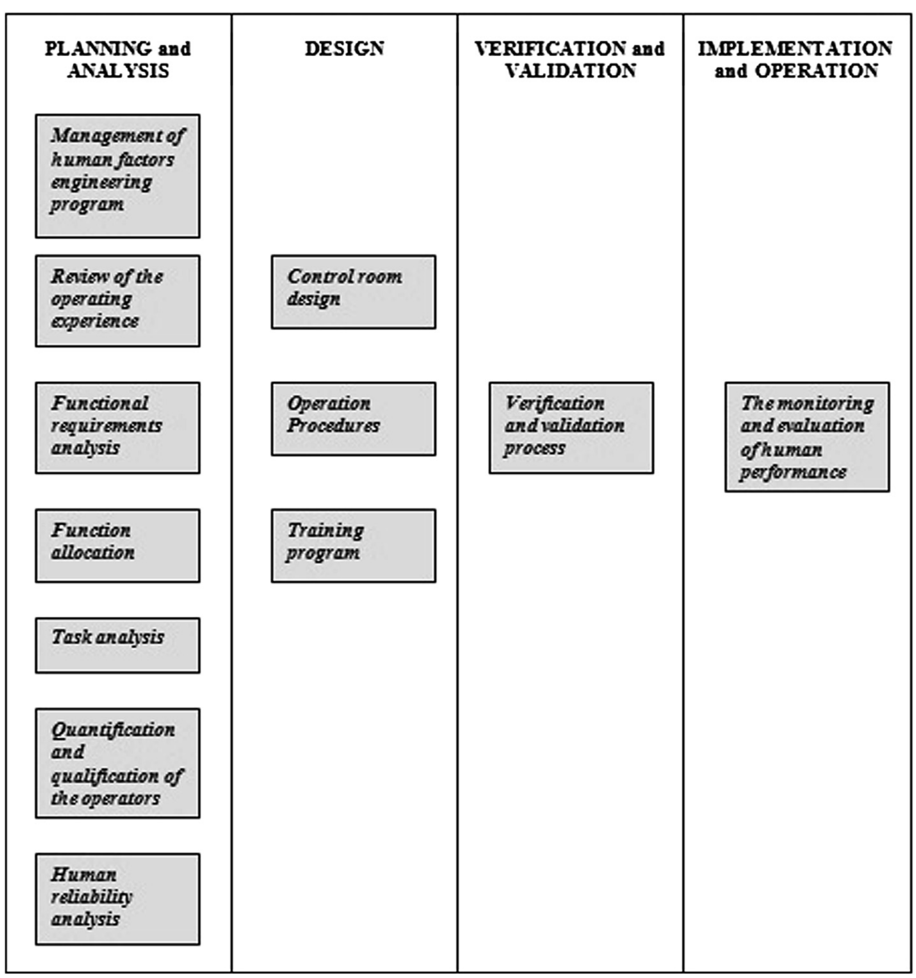

Fig. 1. Human factors engineering program.

important. Markowski, Mannan, and Bigoszewska (2009) used the fuzzy sets theory for accident scenario risk assessment. A typical case study comprising a fault tree for rupture of the isobutane storage tank was performed and a comparison between the traditional approach and fuzzy method was made.

The aim of this paper is to propose a methodological framework applied to nuclear control room evaluation using ergonomic tools, such as participatory ergonomics, design standards and operator activity analysis. Ergonomic approach uncovers a series of important features related to the control room operation that are not detected by the traditional evaluation, based only on the human factors standards. We describe a case study in which the methodology framework was used in the evaluation process of a nuclear control room. The information gathered made possible a series of recommendation for the adequacy of the control room design, assisting operators to run the plant more efficiently, improving plant and operator performance and justifying the alarm panel modernization.

2. Control room evaluation

Countries have established and maintained the necessary regulatory framework to ensure the safety of its nuclear installations. Nuclear installation shall not operate without a license, being necessary a review process, including the documentation to be presented at each phase of the project. The licensing process is divided in several steps: site approval, construction license, authorization for initial operation, authorization for permanent operation and decommissioning. For the first step is necessary to take into account the factors related to the site that might contribute to violation of established dose limits at the proposed exclusion area. For the second step is necessary to perform a detailed review and assessment of the information received from the Preliminary Safety Analysis Report (PSAR). For the initial operation authorization is necessary to review the construction status, including results of pre-operational tests and update the assessment of the plant design based on the information submitted in the Final Safety Analysis Report (FSAR), including the license of the reactor operators.

Human–system interfaces have significant implications in the safety, once they affect the mode that operators search for information related with the status from the main systems, influence the operator activity and determine the necessaries requirements, so that the operators can understand and supervise the main parameters. The actions carried out by the operators are supported through operation procedures, emergency procedures, alarm systems, communication systems, data presentation systems, control systems and safety systems. Human factors standards are based upon partial indications face to contemporary ergonomics issues, not contemplating the inclusion of operator activity analysis in the real workplace. Recent application from complexity theory for work analysis (Marmaras & Pavard, 1999) has emphasized that regulations compose a set of mechanisms strongly relevant for the evaluation of complex systems.

Luquetti dos Santos, Farias, Beany, Falcão, and Marcelino (2011) explained that human centered design emphasizes the use of ergonomics methods to collect human performance data, so that the allocation of user needs in all phases of control room design can be guaranteed. Human centered design should start at the earliest stage of the project and be repeated iteratively until the system meets the requirements.

Alarms are needed in the management of large industrial processes. An alarm should help the operator to diagnose faults. It is a signal indicating a combination of conditions that require the operator's attention. Alarm system developed according to operator's working conditions contributes to maintaining safe and efficient operation. Further, the alarm should require a physical or cognitive response (Sørenssen et al., 2002).

The evaluation process of nuclear control room has recently come into importance due to the recognition of the impact of human performance on system performance and the inadequacy of traditional evaluation methods. According to Hollnagel (1985, pp. 21–26), there are three evaluation methods: conceptual, static and dynamic.

Conceptual evaluation depends on extensive description and knowledge of the system. It can be carried out by experts using some tools as task analysis; operational experience revision; safety analysis reports; design specifications; descriptions of panels, workstation, graphical interfaces and diagrams showing flows of information.

Static evaluation is represented by samples taken from system performance recordings using results of real system operation. It concentrates on the way in which information is presented to the operator and involves some form of interaction between system and operators. One way to use static evaluation is by means of questionnaires, checklists and human factors guidelines. The advantage of this method is that it can use the expert knowledge.

The dynamic evaluation requires a detailed experimental planning, including training, data gathering, analysis system (process state, process events), log of operator actions (human machine interfaces, keyboard, touch screen) and audio, video recorder (verbal protocols, communication). The process is simulated, the operators have a degree of psychological involvement and they react to the simulated process in a realistic manner. Full-scope simulation have some important features that can be distinguished from field studies, being possible some control of the experiment or introduction of transients that would be difficult to perform in the real world situation. It is not possible the introduction of special factors as safety culture and managerial practices. During field study, operator activity analysis is understood through observation in terms of gestures and postures, where the observer locates classes of behavior that are recognizable and repeated during work (Faverge, 1980). This analysis is based on what is observed, conversations and what is not said. It allows the observers to identify not only actions related to prescribed work, but also side activities which are either explicit (but not formulated in the frame of the task description) or implicit. Implicit activities may be unconsciously done by operators. Implicit activities are in many ways the reason of cooperative work. What is discovered, through direct observation or with the aid of cameras or recorders, is a set of signals picked up by the operators in the information field (Marmaras & Pavard, 1999).

3. Methodological framework

In this item, the main phases of the methodological framework are shown in Fig. 2.

The first phase concerns multidisciplinary team formation. According to Luquetti dos Santos et al. (2011), participatory ergonomics is an approach that involves experts and workers actively engaged in system development and in the analysis of ergonomics problems. The success of this approach is directly related to the strength of group involvement. It is important that the group realize the importance of participating in the process, to recognize that the workers are experts at their jobs and that they can provide valuable insight into design problems. This phase refers to the profile of the multidisciplinary team. The team included one human factors expert, one electronic engineer and two operators. The human factors expert is an engineer with fifteen years of experience in nuclear instrumentation design and ten years of experience

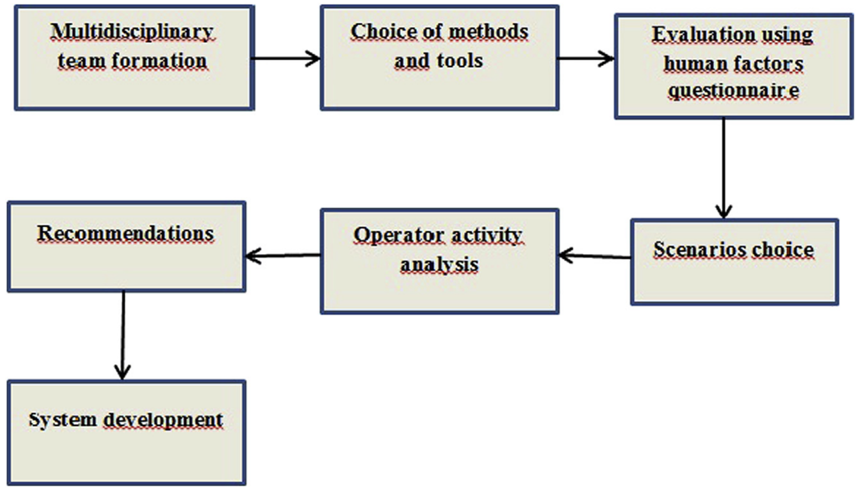

Fig. 2. Methodological framework.

in ergonomic evaluation of nuclear control room. The electronic engineer has fifteen years of experience in nuclear instrumentation design. The control room operators are licensed operators with fifteen years of experience in the operation of research nuclear reactors.

The tasks and responsibilities must be assigned to each team member according to their technical capabilities. The human factors expert is the leader of the team, responsible by coordination and management of the conflicts relative to team preferences. The electronic engineer is responsible for tests and development related to nuclear instrumentation modernization. Operators provided information to team members in response to questions related to their work activities, needs, work practices and control room operation.

The second phase concerns choice of methods and tools used in the evaluation process of nuclear control room. The methods and tools were selected based on what kind of information they provide, on what kind of information the team could use and on what ergonomics methods could generate more high-quality descriptive and predictive databases. Firstly, the multidisciplinary team decided to use a human factors questionnaire adapted from the questionnaire developed by Dos Santos, Grecco, Mol, and Carvalho (2009). The human factors questionnaire was chosen because it is a reliable method of research, that makes available a large group of results in a condensed format, relatively quick to use and easy to interpret the results. The familiarization of the operators with the structure of the questions and the training received previously also influenced the choice of the human factors questionnaire.

The operator activity analysis was the second tool chosen by the multidisciplinary team.

The primary goal of any work analysis is to describe what the operator does, placing it more precisely into its work environment, describing the elements of the context that seem to influence the operator behavior. Based on the scenarios chosen, work analysis is carried out and interaction between the operator and systems is described. It requires a detailed planning, including data gathering, data analysis and audio, video recorder.

The fourth phase is related to the choice of the scenarios. The multidisciplinary team decided to use the results of the human factors questionnaire as inputs in the scenarios choice process. The human factors questionnaire identifies questions and requirements that are not in compliance with the human factors guideline – NUREG 0700 (2002), such as alarms, controls, panel layout and panel label problems. The scenario choice was performed by the multidisciplinary team. The scenarios chosen were performed by the operators and through operator activity analysis the data related to operator performance were collected and analyzed.

At the end of operator activity analysis, the multidisciplinary team identified and analyzed the human factors issues. Recommendations were included in the modernization of the control room.

The last phase is named development. In this phase, recommendations suggested were incorporated in the system development.

4. Material and methods

In this item, we describe the use of the methodological framework applied to evaluation of a nuclear control room.

4.1. Field study

The research nuclear reactor is open pool and uses enriched uranium. It was designed to operate at low power, allowing easy access to experimental facilities. In the current core configuration, the reactor is being operated within the power range 170–370 Watts. The principal area of the nuclear reactor comprises the main control room, researchers' room and reactor hall.

In the main control room, the operator monitors and controls the nuclear process, recognizes disturbances that affect safety and maintains the plant in safe conditions. The main control room is subdivided into following sections (Fig. 3):

- control desk;
- safety system and nuclear instrumentation. They are positioned on the right side of the control console;
- communication system, physical monitoring system and fire prevention system. It is positioned on the right side of the control console and close to safety rack and nuclear instrumentation rack;
- process instrumentation and radiation monitoring. It is positioned on the left side of the control console.

In the control desk, there are strip paper recorders that show the variables evolution of the power channels; analogue meters that show data related to pulse, linear and power channels; conductivity meters; area radiation meters; and electronic modules. The operational parameters of the reactor are monitored by one operator

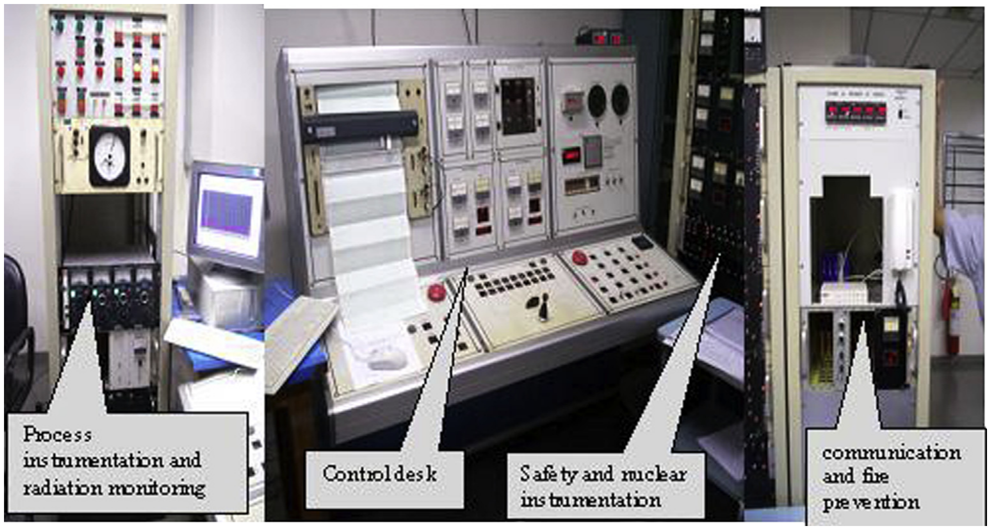

Fig. 3. Main control room.

located at the reactor control desk. There is only one control desk in the control room.

The control room crew is composed of two licensed operators. One of them is responsible for the diary operation of the reactor. Another one is the support operator. The operators' age typically range from 35 to 45 years, and have more than 15 years of experience in nuclear operation. Aiming to protect the operators and in accordance with safety standards established by the licensing sector, the control room walls are shielded and isolated from the reactor hall.

4.2. Human factors questionnaire

Dos Santos et al. (2009) developed a questionnaire for the verification of human factors requirements in the nuclear control desk design. The human factors questionnaire consisted of questions related to five areas, such as panel layout, panel label, information displays, controls and alarms. In our study, we propose a methodological framework applied to nuclear control room evaluation using multidisciplinary team, human factors questionnaire adapted from Dos Santos et al. (2009) and operator activity analysis. The adapted questionnaire consists of questions related to the same five areas cited above, including another area called working environment. The results were used as inputs during the scenarios choices. In this way, scenarios performed by operator enabled the identification of actions that exhibit higher-level cognitive activity and suggest systems to be modernized, such as alarm panel.

In this research, the questionnaire framework shown in Fig. 4 was developed. The questionnaire has been structured to cover six areas, such as: panel layout, panel label, information displays, controls, alarms and working environment. Sixteen questions are related to panel layout (controls and displays arrangement, control–displays relationships and demarcation of panel layout). Ten questions are related to panel label (labels formats, identification of units, consistent wording and separation). Six questions are related to information displays (scaling conventions, numbering of scales and uniformity of measurements units). Seven questions are related to controls (pushbuttons, continuous adjustment controls, thumbwheels, toggle switches, size uniformity and indication of actuation). Eleven questions are related to alarms (indication, location and configuration). Eight questions are related to working environment (workstation design, comfort, temperature, lighting level, acoustics, vibrations and noise level). The score of the human factors questionnaire is defined as the value of the conformance scale multiplied by the importance weights, Eq. (1).

$$\text{Score} = \text{Conformance scale} \times \text{Importance weights} \tag{1}$$

Each feature of the control room is rated on a conformance scale, shown below:

0: the requested design feature is complied with the human factors guideline;
1: the requested design feature is partially complied with the human factors guideline;
2: the requested design feature is not complied with the human factors guideline.

Since some features may be more important than others, importance weights can be assigned. The importance weights are:

3: the feature is mandatory;
2: the feature is desirable;
1: the feature is not important.

The score equals zero or 1 is related to low risk (L), 2 or 3 is related to moderate risk (M), and 4 or 6 is related to high risk (H).

The human factors questionnaire is shown in Fig. 4. The item named AREA identifies one of the six areas: panel layout, panel label, controls, alarms, working environment and information displays. The questions related to the six areas are included in the item QUESTIONS. The explanations related to the questions are included in the item INFORMATION. The conformance scale, the importance weight and the score result are included in the item called SCORE. The identification of the nuclear risk as high (H), moderate (M) or low (L) is presented in the item named RISK. The item named RESULTS, represented as Eq. (2), presents the percentage of questions evaluated as high risk (H). The number of questions evaluated as high risk is defined as HR. The number of questions for each area is defined as NQ. For the panel layout, NQ is equal to 16. For the panel label, NQ is equal to 10. For the information displays, NQ is equal to 6. For the Controls, NQ is equal to 7. For the alarms, NQ is equal to 11. For the working environment, NQ is equal to 8.

$$\text{RESULTS} = (\text{HR}/\text{NQ}) \times 100\% \tag{2}$$

AREA	QUESTIONS	INFORMATION	SCORE			RISK		
			SCALE 0: Completely complied 1: Partially complied 2: Not complied WEIGHTS 1: Not important 2: Desirable 3: Mandatory			Score / RISK 0 or 1 / L 2 or 3 / M 4 or 6 / H		
			Scale	Weights	Score	L	M	H
Inf. Displays	1.							
	2.							
	3.							
	4.							
	5.							
	6.							
RESULTS = (HR / NQ) x 100%								

Fig. 4. Human factors questionnaire.

The multidisciplinary team was trained on the use of the human factors questionnaire, focusing on the familiarization with the questions. The team was asked to fill in the conformance scale and the importance weights for the questions related to panel layout, panel label, information displays, controls, alarms and working environment. The item RESULTS identified the areas with the highest percentages of questions considered as high risk (H), that were not in compliance with NUREG 0700 (2002). The multidisciplinary team discussed the results and decided to choose scenarios that included the area considered as priority and the respective questions evaluated as high risk (H).

The item SCORE was calculated and the identification of the nuclear risk (high, moderate or low) was presented in the item RISK (Fig. 4). The Cohen's Kappa index (Fleiss & Cohen, 1973) was used to assess the agreement level, related to item RISK, between two observers (inter-rater agreement). Numbers of agreements between the multidisciplinary team were quantified and the Cohen's Kappa index was calculated.

4.3. Scenarios choice

According to Venable, Li, Ginter, and Duncan (1993), scenarios usually include important situations and problems that exist in some context form. It involves the recognition that many factors may combine in complex ways to create situations and problems that can affect the human ability to handle normal and abnormal situations.

The multidisciplinary team discussed the human factors questionnaire results in an environment that supported free exchange of experience. The results assisted the multidisciplinary team in the choice of the scenarios, indicating the areas that could be incorporated in the scenarios. The multidisciplinary team selected two scenarios that cover a broad spectrum of factors, based on the results of the human factors questionnaire. The process of constructing scenarios was very important, because it provided the basis for the identification of weak points in the control room design and established a discussion about factors that affect operator performance.

4.4. Operator activity analysis

It was carried out through structured observations and interviews, considering the scenarios chosen by the multidisciplinary team. The data collection has been effected through field notes, fixed video cameras and photographs. The goal was to identify human factors problems in the control desk design; whether information about operation was sufficient and available; and identify the following cognitive functions: monitoring/detection; situation assessment; response planning; response implementation (Hollnagel, 1998, chap. 9; Rasmussen, 1983). The monitoring/detection address observation and identification of signals, information and data received by the operator. Situation assessment describes how the operator interpreted and organized information into a meaningful whole, in order to construct a coherent and logical explanation to account for the observations. Situation model is a mental representation that integrates operator understanding about physical and functional aspects of the plant and plant systems (Mumaw, Swatzler, Roth, & Win, 1995). Situation model is constantly updated as new information is received and operator understanding of situation changes. Response planning refers to the process of making a decision. It involves operator using situation model of the current plant state to identify goals, generate alternative response plans, evaluate response plans, and select the most appropriate response plan. Response implementation refers to execution of the planned actions required to perform a task.

5. Results

In this chapter results are presented.

5.1. Questionnaire results

The human factors expert (HE), electronic engineer (EE) and the operators (O1 and O2) filled in the answers for the questions presented in the questionnaire (Fig. 4). The agreement level of the answers evaluated as high risk among the operator one and operator two (O1/O2), operator one and human factors expert (O1/HE),

Table 1
Cohen's kappa test.

Team	The kappa value (*K*)
O1/O2	0.78
O1/HE	0.77
O1/EE	0.76
O2/HE	0.77
O2/EE	0.76
HE/EE	0.76

Table 2
Results of human factors questionnaire.

Area	Results = (HR/NQ) × 100%
Panel layout	0%
Panel label	20%
Information displays	0%
Controls	14%
Alarms	64%
Working environment	12.5%

operator one and electronic engineer (O1/EE), operator two and human factors expert (O2/HE), operator two and electronic engineer (O2/EE), human factors expert and electronic engineer (HE/EE) were quantified using the Cohen's kappa statistics. The results of the Cohen's kappa test (K) were greater than 0.75 (Table 1). It means that the degree of agreement among the multidisciplinary team was good (Fleiss & Cohen, 1973). It gave an indication of the consistency of the evaluation results and that the use of the human factors questionnaire made possible the identification of a set of design problems and recommendations.

The areas and the questions evaluated as being of high risk (H) were selected and considered during the scenarios choice. The results are shown in the Table 2.

5.2. Scenarios chosen

The following requirements were used for scenarios choice: scenarios involving issues related to operation safety and scenarios that incorporate an specific array of variables based on the human factors questionnaire (alarms, controls, panel label and working environment), according to their probability of occurrence and likely impact on the operation safety. Through meetings, the multidisciplinary team discussed the selection and description of the scenarios. Two scenarios were chosen. The first one is related to reactor start-up and increase in reactor power up to the level of eighty percent of nominal power (scenario one). The second one is related to the start-up and reactor shutdown due to alarm in the gamma radiation monitoring device, located in the reactor hall.

5.3. Operator actions

The analysis was based on observations of the operator performance under two scenarios. The human factors expert observed how the operator interacted with the nuclear reactor systems. The human factors expert paid particular attention to the operator tasks, searching for deficiencies in operator response to normal and abnormal situations. The analysis focused on how the systems have supported situation awareness and decision making.

Interviews were carried out with the operator at the end of each observation period, where critical decisions and strategies made by the operators during scenarios were reviewed. One fixed video camera and a hand-held digital camera were used to support data collection. The data collected consists of a total of six hours of observation (three days of observation, two hours per day) including startup tests, reactor startup, increase in reactor power up to the level of eighty percent of nominal power and reactor shutdown.

In this phase, the operator monitoring model (Fig. 5), adapted from the Mumaw et al. (1995) model, was used. This model has three major elements: Initiating events, operator cognitive

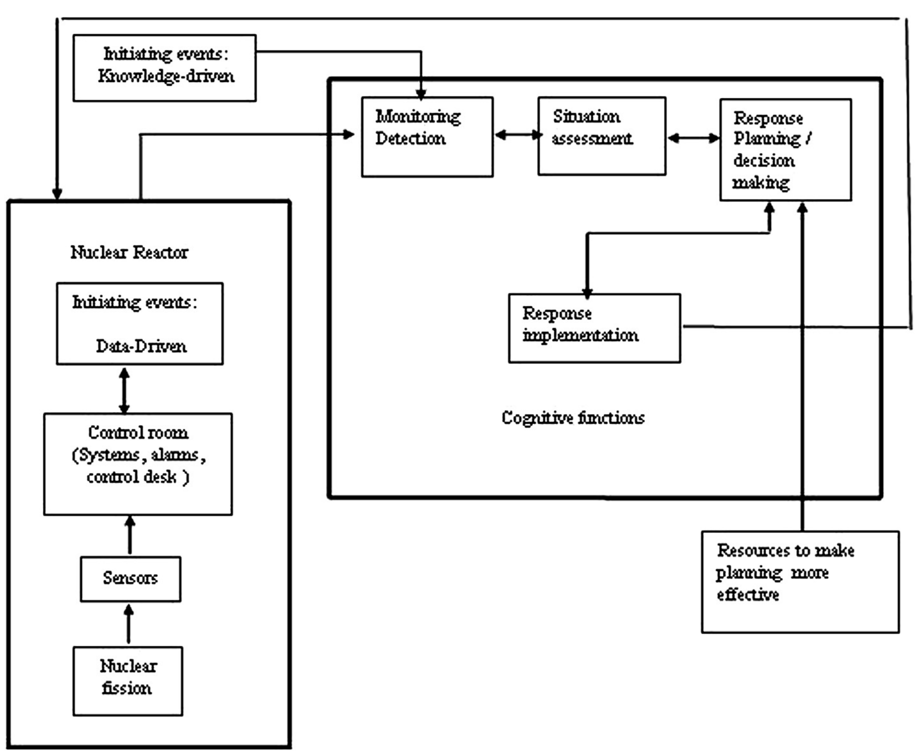

Fig. 5. Operator monitoring model.

Table 3
Scenario one.

Operator actions
1.0 Turn on power supply of the control desk
2.0 Check (Evaluate) indicator lamps 2.1 Observe indicator lamp "POWER SUPPLY" is ON 2.2 Observe indicator lamp "NEUTRON SOURCE IN" is OFF
3.0 Check (Evaluate) data from nuclear instrumentation 3.1 Observe the analogue meters of the pulse channel located in the control desk: counts less than 10 pulses per second 3.2 Observe the analogue meters of the power channel located in the control desk: no power
4.0 Record water conditions 4.1 Temperature 4.2 PH 4.3 Resistivity
5.0 Put the operation key in the position "SOURCE" 5.1 Put the joystick control in the up position and insert the neutron source 5.2 Observe indicator lamp "NEUTRON SOURCE IN" is ON
6.0 Check (Evaluate) data from nuclear instrumentation 6.1 Observe the analogue meters of the pulse channel located in the control desk: counts greater than 10 pulses per second 6.2 Observe the analogue meters of the power channel located in the control desk: no power
7.0 Put the joystick control in the position "SAFETY ROD NUMBER 1" 7.1 Put the joystick control in the up position and remove the safety rod number 1 of the reactor core 7.2 Observe indicator lamp "SAFETY ROD NUMBER 1" is OFF
8.0 Put the joystick control in the position "SAFETY ROD NUMBER 2" 8.1 Put the joystick control in the up position and remove the safety rod number 2 of the reactor core 8.2 Observe indicator lamp "SAFETY ROD NUMBER 2" is OFF
9.0 Put the joystick control in the position "SAFETY ROD NUMBER 2" 9.1 Put the joystick control in the up position and remove the safety rod number 3 of the reactor core 9.2 Observe indicator lamp "SAFETY ROD NUMBER 3" is OFF
10.0 Turn on the power switch of the drain valve 10.1 Put the joystick control in the position "DRAIN VALVE" 10.2 Close "DRAIN VALVE" 10.3 Observe indicator lamp "DRAIN VALVE CLOSED" is ON 10.4 Put the joystick control in the position "WATER LEVEL"
11.0 Turn on the power supply of the main pump 11.1 Observe indicator lamp "MAIN PUMP" is ON 11.2Observe indicator lamp "WATER LEVEL HIGH" is ON
12.0 Check (Evaluate) data from nuclear instrumentation 12.1 Observe the analogue meters of the pulse channel located in the control desk: counts increasing 12.2 Observe the analogue meters of the power channel located in the control desk: no power
13.0 Turn on the key called "CONTROL RODS" 13.1 Observe indicator lamp "CONTROL RODS" is ON 13.2 Observe indicator lamp "CONTROL RODS IN" is ON
14.0 Put the operation key in the position "APPROXIMATE CONTROL ROD" 14.1 Put the joystick control in the up position and remove the approximate control rod of the reactor core 14.2 Observe indicator lamp "APPROXIMATE CONTROL ROD IN" is OFF
15.0 Check (Evaluate) data from nuclear instrumentation 15.1 Observe the analogue meters of the pulse channel located in the control desk: counts equal to 10,000 counts per second 15.2 Observe the analogue meters of the power channel located in the control desk: power increasing
16.0 Turn off the high voltage power supply of the pulse channel
17.0 Observe the analogue meters of the **gamma radiation monitors**
18.0 Put the operation key in the position "COARSE CONTROL ROD" 18.1 Put the joystick control in the up position and remove the coarse control rod of the reactor core 18.2 Observe indicator lamp "COARSE CONTROL ROD IN" is OFF
19.0 Observe the analogue meters of the **gamma radiation monitors**
20.0 Put the operation key in the position "ACCURATE CONTROL ROD" 20.1 Put the joystick control in the up position and remove the accurate control rod of the reactor core 20.2 Observe indicator lamp "ACCURATE CONTROL ROD IN" is OFF
21.0 Observe the analogue meters of the **gamma radiation monitors**
22.0 Monitor power channel 22.1 Observe the analogue meters of the power channel are measuring eighty (80%) power 22.2 Observe nuclear reactor power does not decrease and remains at eighty (80%) power

functions and resources to make monitoring more effective. According to Mumaw et al. (1995), two types of triggers initiate monitoring. The first category is called "data-driven events" that comprise indication received through meters, sensors, interfaces; visual and auditory alarms from control room. The second category is called "Knowledge-driven events" defined by a set of standard practices or plant procedures, such as written records of instrumentation tests and significant alarms; scheduled tasks; work permits; information about equipment taken out of service and formal check procedures.

In this phase, the purpose was to produce a summary of actions as they have been carried out by the operators. In order to ensure the reliability of the actions description, we used different sources of information, such as operating manuals, diary operation register and the data collected through operator activity analysis. In scenario one, the description of the actions carried out by operator is shown in Table 3. In scenario two, the description of the actions carried out by operator is shown in Table 4.

Using Mumaw et al. (1995) model, scenario one and scenario two were analyzed. The purpose was to identify actions where the operator exhibited higher-level cognitive activity and suggest systems that could be modernized, in order to support cognitive process activities. According to Hollnagel (1998, chap. 9) and Vicent and Burns (1996), the purpose of a cognitive demand profile is to indicate whether operator actions as a whole are likely to depend on a specific set of cognitive functions. If so, the conditions where these cognitive functions are required should be further analyzed. The description of the operator actions sequence (Tables 3 and 4) is refined by identifying the cognitive functions that characterize each action (Figs. 6 and 7).

As it can be seen from Fig. 6, the first segment of the actions carried out by the operator is called initial verification. It involves the actions number one up to number four. It is dominated by monitoring (40%) and situation assessment (30%), involving little response planning (20%) and response implementation (10%). The second segment of the actions is called start-up. It involves the actions number five up to number twelve. It is dominated by response implementation (46.43%) and monitoring (39.29%), involving little situation assessment (7.14%) and response planning (7.14%). The third segment of the actions is called increase reactor power. It involves the actions number thirteen up to number twenty-two. It is dominated by monitoring (54.17%) and response implementation (33.33%), involving little situation assessment (2.33%) and response planning (4.17%). For verification initial, the results suggest that the modernization of systems related to monitoring and situation assessment can improve operator performance. For start-up, the results suggest that the modernization of systems related to response implementation and monitoring can improve operator performance. For increase reactor power, the results suggest that the

Table 4
Scenario two.

Operator actions
1.0 Turn on power supply of the control desk (Execute)
2.0 Check indicator lamps 2.1 Observe indicator lamp "POWER SUPPLY" is ON 2.2 Observe indicator lamp "NEUTRON SOURCE IN" is OFF
3.0 Check data from nuclear instrumentation 3.1 Observe the analogue meters of the pulse channel located in the control desk: counts less than 10 pulses per second 3.2 Observe the analogue meters of the power channel located in the control desk: no power
4.0 Recorder water conditions 4.1Temperature 4.2 PH 4.3 Resistivity
5.0 Put the operation key in the position "SOURCE" 5.1 Put the joystick control in the up position and insert the neutron source 5.2 Observe indicator lamp "NEUTRON SOURCE IN" is ON
6.0 Check data from nuclear instrumentation 6.1 Observe the analogue meters of the pulse channel located in the control desk: counts greater than 10 pulses per second 6.2 Observe the analogue meters of the power channel located in the control desk: no power
7.0 Put the joystick control in the position "SAFETY ROD NUMBER 1" 7.1 Put the joystick control in the up position and remove the safety rod number 1 of the reactor core 7.2 Observe indicator lamp "SAFETY ROD NUMBER 1" is OFF
8.0 Put the joystick control in the position "SAFETY ROD NUMBER 2" 8.1 Put the joystick control in the up position and remove the safety rod number 2 of the reactor core 8.2 Observe indicator lamp "SAFETY ROD NUMBER 2" is OFF
9.0 Put the joystick control in the position "SAFETY ROD NUMBER 3" 9.1 Put the joystick control in the up position and remove the safety rod number 3 of the reactor core 9.2 Observe indicator lamp "SAFETY ROD NUMBER 3" is OFF
10.0 Turn on the power switch of the drain valve 10.1 Put the joystick control in the position "DRAIN VALVE" 10.2 Close "DRAIN VALVE" 10.3 Observe indicator lamp "DRAIN VALVE CLOSED" is ON 10.4 Put the joystick control in the position "WATER LEVEL"
11.0 Turn on the power supply of the main pump 11.1 Observe indicator lamp "MAIN PUMP" is ON 11.2 Observe indicator lamp "WATER LEVEL HIGH" is ON
12.0 Check data from nuclear instrumentation 12.1 Observe the analogue meters of the pulse channel located in the control desk: counts increasing 12.2 Observe the analogue meters of the power channel located in the control desk: no power
13.0 Switch on the key called "CONTROL RODS" 13.1 Verify indicator lamp "CONTROL RODS" is ON 13.2 Verify indicator lamp "CONTROL RODS IN" is ON
14.0 Put the operation key in the position "APPROXIMATE CONTROL ROD" 14.1 Put the joystick control in the up position and remove the approximate control rod of the reactor core 14.2 Verify indicator lamp "APPROXIMATE CONTROL ROD" is OFF
15.0 Vary the alarm level of the **gamma radiation monitoring** device located in the reactor hall 15.1 Observe alarms indicator from gamma radiation monitoring device is ON 15.2 Verify approximate control rod was introduced automatically in the reactor core 15.3 Verify reactor is shutdown

modernization of systems related to monitoring and response implementation can improve operator performance.

As it can be seen from Fig. 7, the first segment of the actions carried out by the operator is called initial verification. It involves the actions number one up to number four. It is dominated by monitoring (40%) and situation assessment (30%), involving little response planning (20%) and response implementation (10%). The second segment of the actions is called start-up. It involves the actions number five up to number twelve. It is dominated by response implementation (46.43%) and monitoring (39.29%), involving little situation assessment (7.14%) and response planning (7.14%). The third segment of the actions is called increase reactor power. It involves the actions number thirteen up to number fourteen. It is dominated by monitoring (50%) and response implementation (50%), no involving situation assessment and response planning. The fourth segment of the actions is called reactor shutdown. It involves the actions number fifteen. It is dominated by monitoring (57.14%), situation assessment (28.57%), involving little response implementation (14.29%), no involving response planning. For verification initial, the results suggest that the modernization of systems related to monitoring and situation assessment can improve operator performance. For start-up, the results suggest that the modernization of systems related to response implementation and monitoring can improve operator performance. For increase reactor power, the results suggest that the modernization of systems related to monitoring and response implementation can improve operator performance. For reactor shutdown, the results suggest that the modernization of systems related to monitoring and situation assessment can improve operator performance. The results are shown in Table 5

Direct or indirect operator support systems can be modernized or added to control desk to support cognitive activities. The most appropriate support system can be selected based on the cognitive process (Lee & Seong, 2007). Information displays, nuclear instrumentation and gamma radiation monitoring system support monitoring. In addition, information displays, nuclear instrumentation and alarms system support situation assessment, enhancing operational efficiency (Fig. 8). The results presented in Fig. 8 and Table 5, associated with human factors questionnaire results and interviews with operators, allowed to recommend the design of a new alarm panel.

5.4. Alarm panel development

In meetings, the multidisciplinary team defined which variables the alarm panel was intended to measure and outlined the design goals. Industrial designer was responsible for the initial sketch of the physical design and details about the information to be presented in alarm panel, given the need to integrate ergonomics requirements into this process. Operators provided information to human factors expert in response to questions related to their needs and difficulties related to operation using information from the old alarms. This step was finished with the definition of functional requirements, presented below:

- the alarm panel will be included in a rack to be positioned on the right side of the control console operator;
- coding scheme used by the alarm panel should assure rapid detection and interpretation by the operators under all control room operating conditions;
- color, position and shape will be employed for priority coding;
- each color should have a single, precise meaning that is consistent with applicable population stereotypes;
- alarms will be indicated both by visual and audible means;
- when the parameter returns to the normal range from an abnormal range, the return to normal conditions will be indicated by visual and audible means;
- alarms should be organized into categories according to priority;

Operator actions	Cognitive demand	Cognitive functions			
		Monitoring	Situation assessment	Response planning	Response implementation
1.0	Execute				■
2.0	Evaluate		■	■	
2.1	Observe	■			
2.2	Observe	■			
3.0	Evaluate		■	■	
3.1	Observe	■			
3.2	Observe	■			
4.0	Record		■		■
5.0	Execute				■
5.1	Execute				■
5.2	Observe	■			
6.0	Evaluate		■	■	
6.1	Observe	■			
6.2	Observe	■			
7.0	Execute				■
7.1	Execute				■
7.2	Observe	■			
8.0	Execute				■
8.1	Execute				■
8.2	Observe	■			
9.0	Execute				■
9.1	Execute				■
9.2	Observe	■			
10.0	Execute				■
10.1	Execute				■
10.2	Execute				■
10.3	Observe	■			
10.4	Execute				■
11.0	Execute				■
11.1	Observe	■			
11.2	Observe	■			
12.0	Evaluate		■	■	
12.1	Observe	■			
12.2	Observe	■			
13.0	Execute				■
13.1	Observe	■			
13.2	Observe	■			
14.0	Execute				■
14.1	Execute				■
14.2	Observe	■			
15.0	Evaluate		■	■	
15.1	Observe	■			
15.2	Observe	■			
16.0	Execute				■
17.0	Observe	■			
18.0	Execute				■
18.1	Execute				■
18.2	Observe	■			
19.0	Observe	■			
20.0	Execute				■
20.1	Execute				■
20.2	Observe	■			
21.0	Observe	■			
22.0	Monitor	■	■		
22.1	Observe	■			
22.2	Observe	■			

Fig. 6. List of cognitive functions (Scenario one).

- six gamma radiation alarms have been defined;
- two alarms of attention related to the operation have been defined.

The alarm panel is presented in Fig. 9.

6. Conclusions

The purpose of this paper was to propose a methodology framework to evaluate nuclear control room, including human factor questionnaire and operator activity analysis, through two

Operator actions		Cognitive demand	Cognitive functions			
			Monitoring	Situation assessment	Response planning	Response implementation
1.0	Initial verification	Execute				■
2.0		Evaluate		■	■	
2.1		Observe	■			
2.2		Observe	■			
3.0		Evaluate		■	■	
3.1		Observe	■			
3.2		Observe	■			
4.0		Record		■		■
5.0	Start-up	Execute				■
5.1		Execute				■
5.2		Observe	■			
6.0		Evaluate		■	■	
6.1		Observe	■			
6.2		Observe	■			
7.0		Execute				■
7.1		Execute				■
7.2		Observe	■			
8.0		Execute				■
8.1		Execute				■
8.2		Observe	■			
9.0		Execute				■
9.1		Execute				■
9.2		Observe	■			
10.0		Execute				■
10.1		Execute				■
10.2		Execute				■
10.3		Observe	■			
10.4		Execute				■
11.0		Execute				■
11.1		Observe	■			
11.2		Observe	■			
12.0		Evaluate		■	■	
12.1		Observe	■			
12.2		Observe	■			
13.0	Increase reactor power	Execute				■
13.1		Observe	■			
13.2		Observe	■			
14.0		Execute				■
14.1		Execute				■
14.2		Observe	■			
15.0	Reactor shutdown	Regulate	■			■
15.1		Observe	■			
15.2		Verify	■	■		
15.3		Verify	■	■		

Fig. 7. List of cognitive functions (Scenario two).

Table 5
Cognitive functions applied to scenario one and two.

Scenario	Operation modes	Systems modernization		
		Monitoring	Situation assessment	Response implementation
1	Initial verification	■	■	
	Start-up	■		■
	Increase power	■		■
2	Initial verification	■	■	
	Start-up	■		■
	Increase power	■		■
	Reactor shutdown	■	■	

The gray shading explains that during the scenarios one and two and operations mode which cognitive functions were used.

scenarios chosen by the multidisciplinary team. The results suggest that the operator activity analysis associated with human factors questionnaire can be used as a support tool to the evaluation process. In this paper, the overall results showed a positive and significant contribution of multidisciplinary team. It reflects the importance of having a group of professionals from diverse disciplines, with different technical formation, who together provides decisions, actions, coordination and assists in the choice of scenarios. The design solutions were made considering the appropriate use of the control room, emphasizing that work practices should be based on the notion that the human is the most important link in complex socio-technical systems. What we really need are control rooms that support actions of the operators. To do so, control rooms must be designed considering that the users need to be taken account in all the phases of the design process. In order to design useful operator support systems, human cognitive process

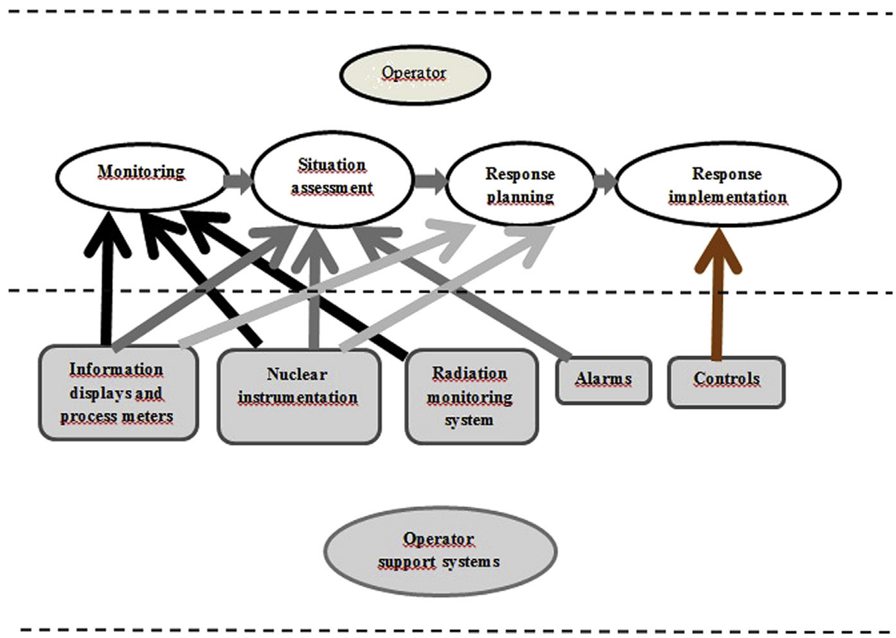

Fig. 8. Systems modernization based on cognitive process model.

model must be analyzed. The results supported the view that cognitive functions (monitoring, situation assessment, response planning and response implementation) have implications for the development and modernization of operator support system. The use of methodological framework made possible a series of recommendation for the adequacy of the control room design, assisting in the identification of ergonomics problems in the panel label, controls, working environment and alarms, and whether sufficient information was available to allow operator to make decisions when required. The findings assisted in the safety assessment of the control room design and were used as a basic for recommendations, justifying the alarm panel modernization.

Future plans include the use of quantitative analysis methods, such as AHP and fuzzy set theory, for the identification and prioritization of non-compliant ergonomic criteria related to control room design. Through the development of a computational tool, based on the human factors questionnaire, will be possible to rank the experts based on professional experience and identify among the design problems evaluated as high risk, which will be corrected with a higher priority.

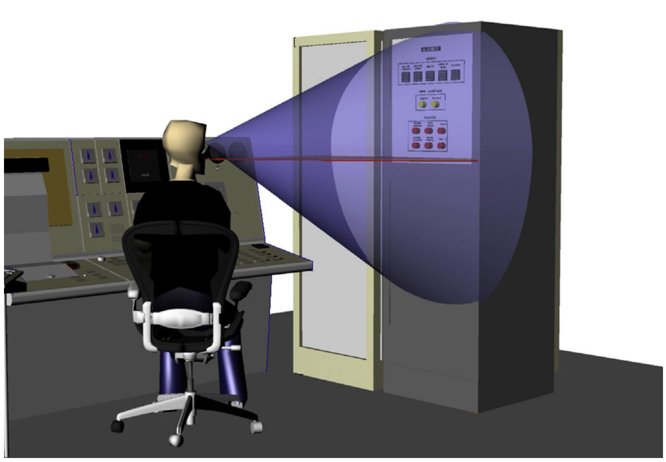

Fig. 9. Alarm panel 3D model.

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